# Wave and Tidal Power: Projects and Prospects

by

**George Hagerman**
hagerman@vt.edu

Virginia Tech
Center for Energy and the Global Environment

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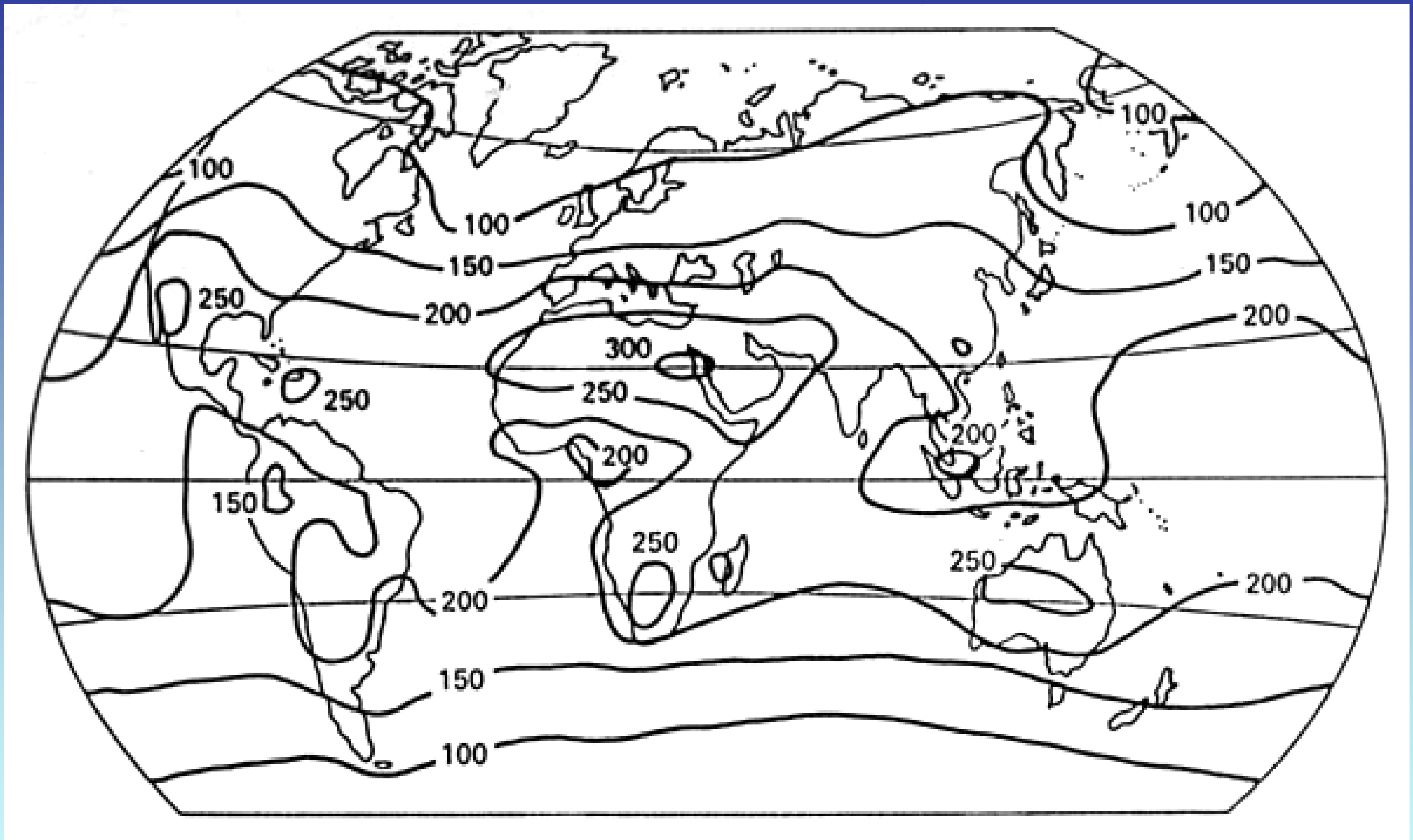
# Presentation Outline

- **Wave Energy Resource**: A derived form of solar energy, in that unequal solar heating of the earth's surface generates wind, and wind blowing over water generates waves.
- **Wave Energy Conversion Devices**: Three categories:
  - Terminator (OWC = oscillating water column, overtopping reservoir)
  - Attenuator (*Pelamis*)
  - Point Absorber (Heaving buoy, submerged float)
- **Tidal Energy Resource**: Astronomically-governed and thus highly predictable and relatively insensitive to weather conditions.
- **Tidal In-Stream Energy Conversion Devices**: Submerged turbine on monopile foundation has made most progress.
- **Electric Power Research Institute Projects**: Multi-year, collaborative efforts leading from feasibility definition study to design, construction, and operation of 500 kW demonstration projects:
  - Offshore Wave Energy Conversion (HI, WA, OR, SF, MA, ME)
  - Tidal In-Stream Energy Conversion (AK,WA, SF, MA, ME, NB, NS)
  - Hybrid Offshore Wind and Wave Energy Conversion (proposed)

# Global Solar Energy Distribution




The highest annual average solar energy flux at sea level is 300 watts per sq.m of horizontal area (*i.e.,* solar cell surface area). At top of Earth's atmosphere, the maximum solar energy flux available to orbiting satellites with sun-tracking solar panels is ~1,370 watts per sq.m.

# Winds Move ~60% of Excess Solar Energy from Equator to Poles

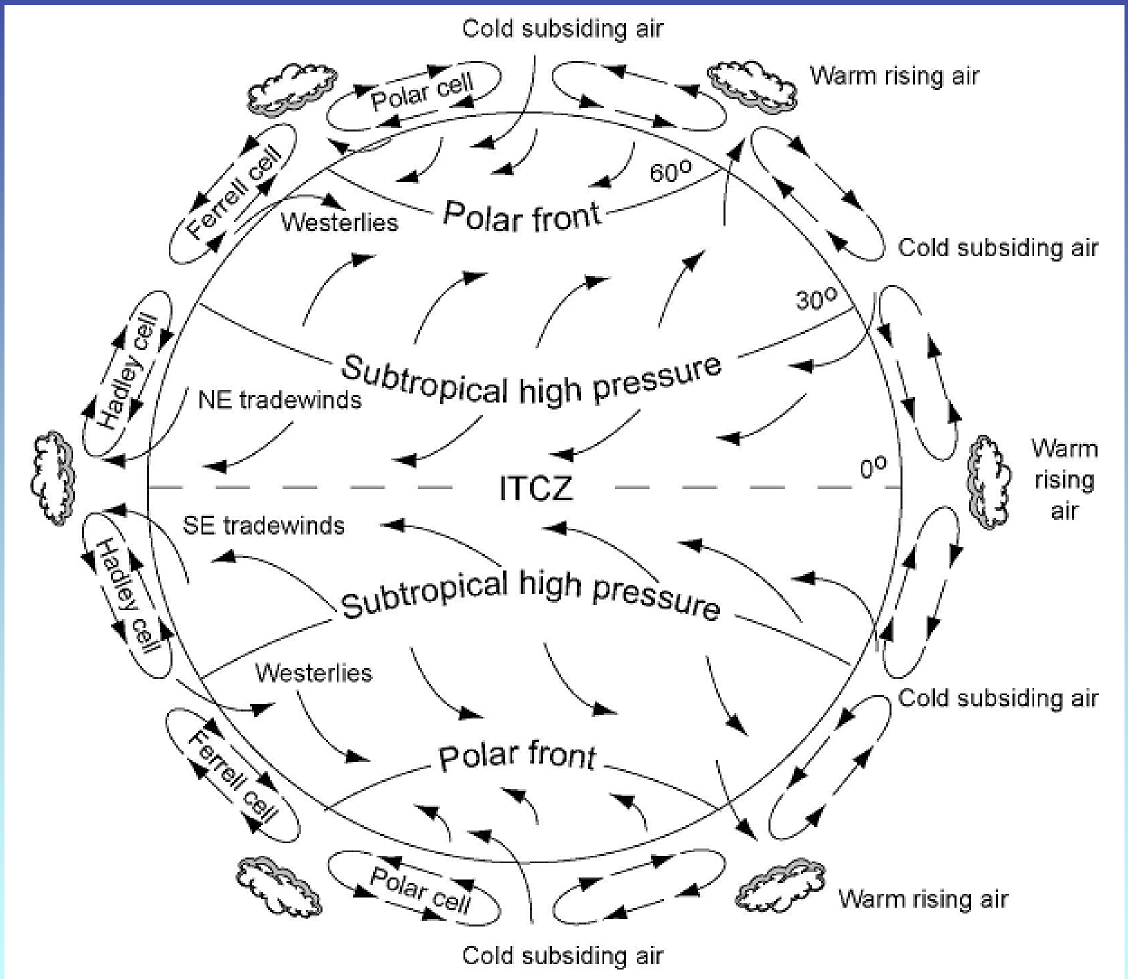
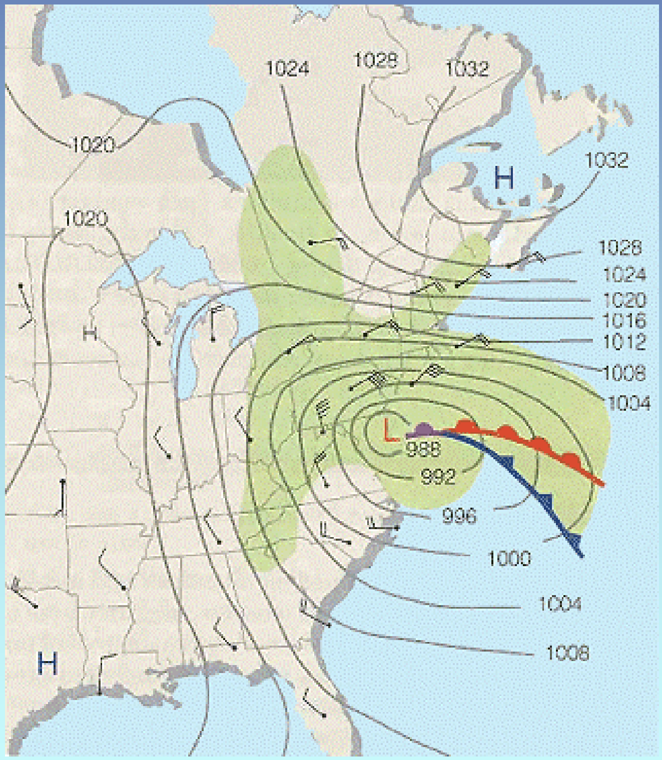
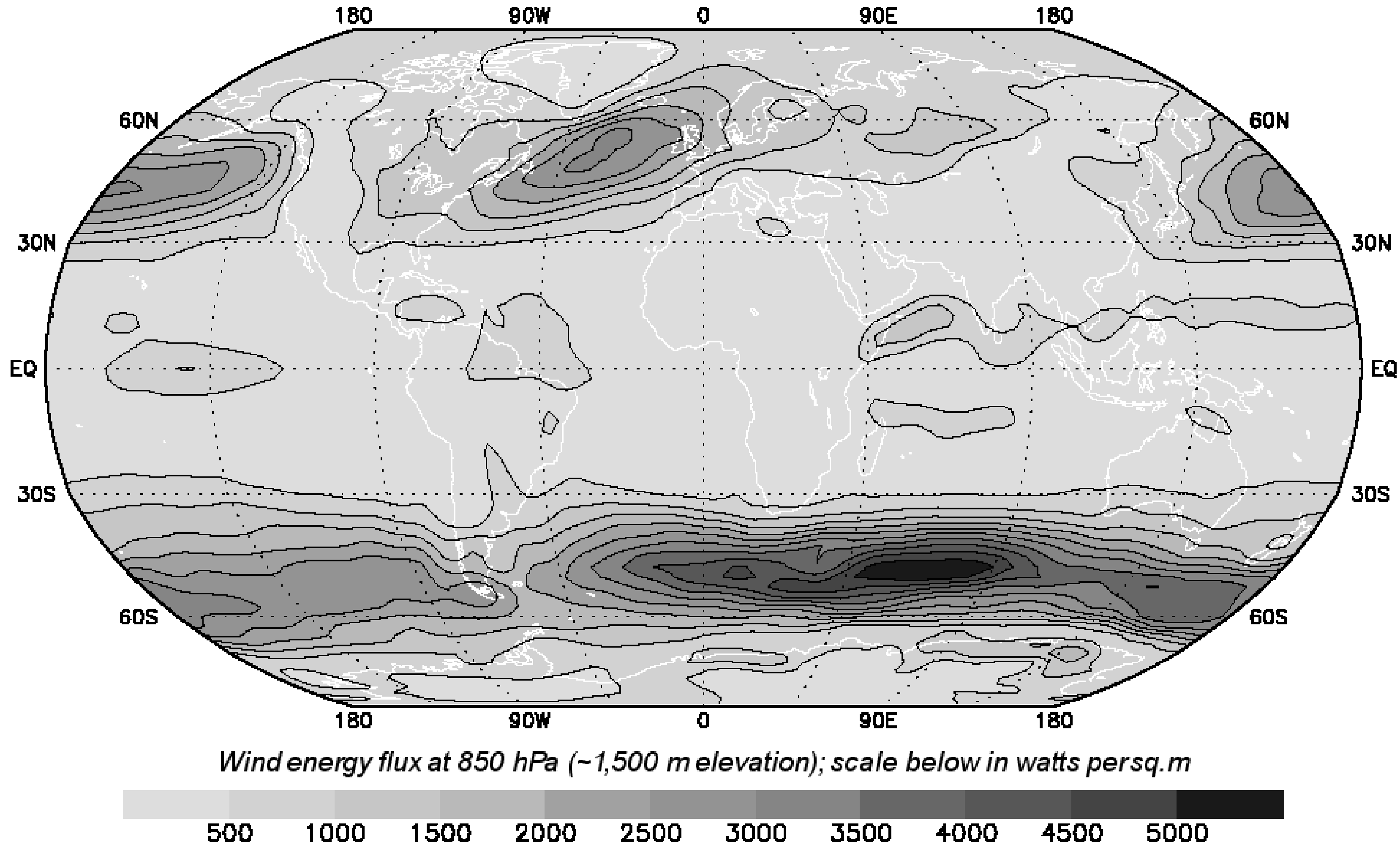



**Figure below shows nor'easter forming as cold dry air picks up heat and moisture from ocean.**




Deep-ocean currents move the remaining ~40% (via thermohaline "conveyer belt").

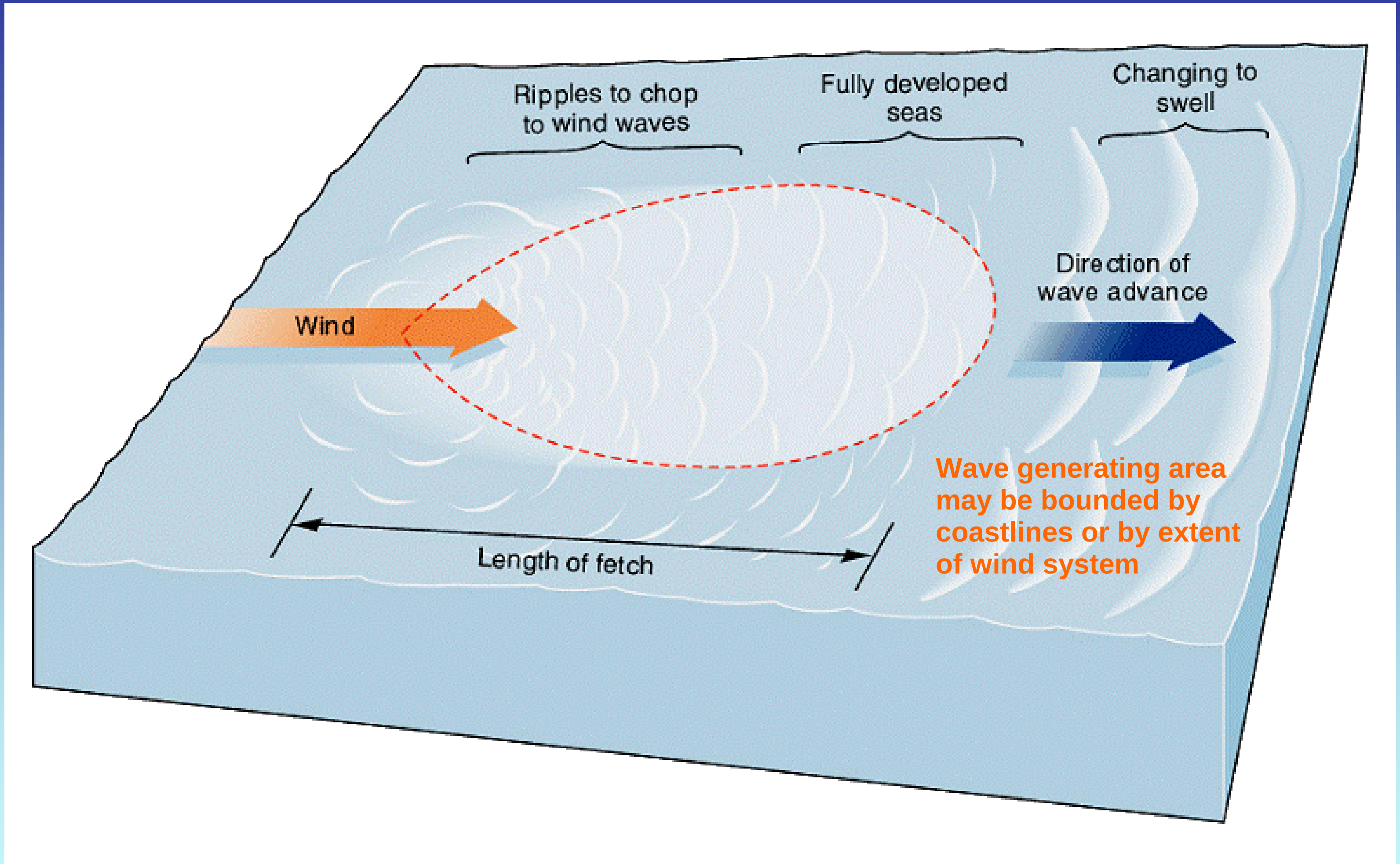
# Global Wind Energy Distribution




*Wind energy flux at 850 hPa (~1,500 m elevation); scale below in watts per sq.m*

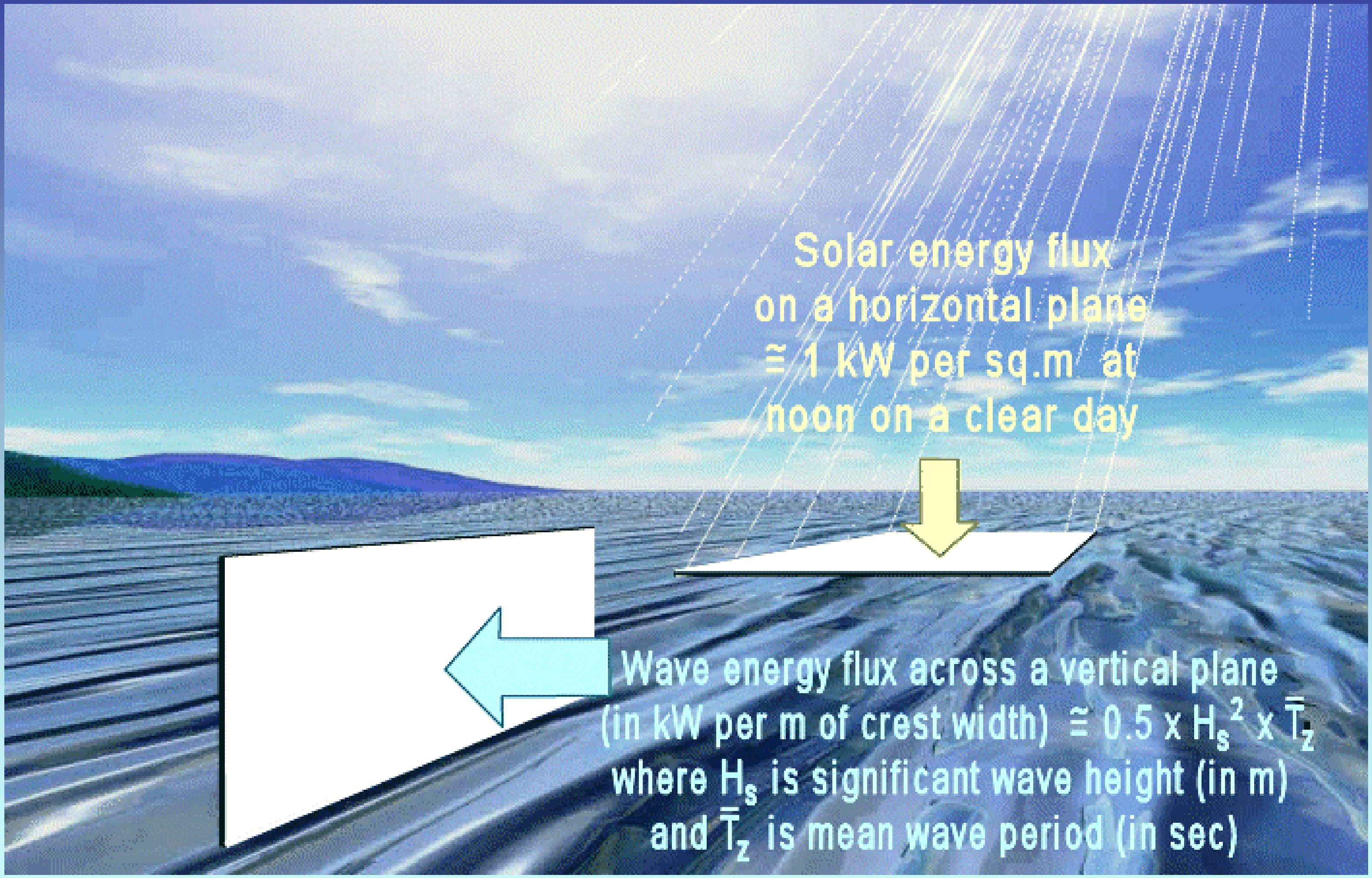
The highest average wind energy flux at the top of the Planetary Boundary Layer is 5,000 watts (5 kilowatts) per sq.m of vertical area (*i.e.* turbine rotor swept area).

# Wind Over Water Generates Waves




Ocean swell can travel thousands of kilometers in deep water with negligible loss of energy. Thus wave energy produced anywhere in an ocean basin ultimately arrives at its continental shelf margins, virtually undiminished until it reaches ~200 m depths.

# Calculation of Wave Energy Flux Density



# Wave Energy Flux in Typical U.S. Mid-Atlantic Sea State

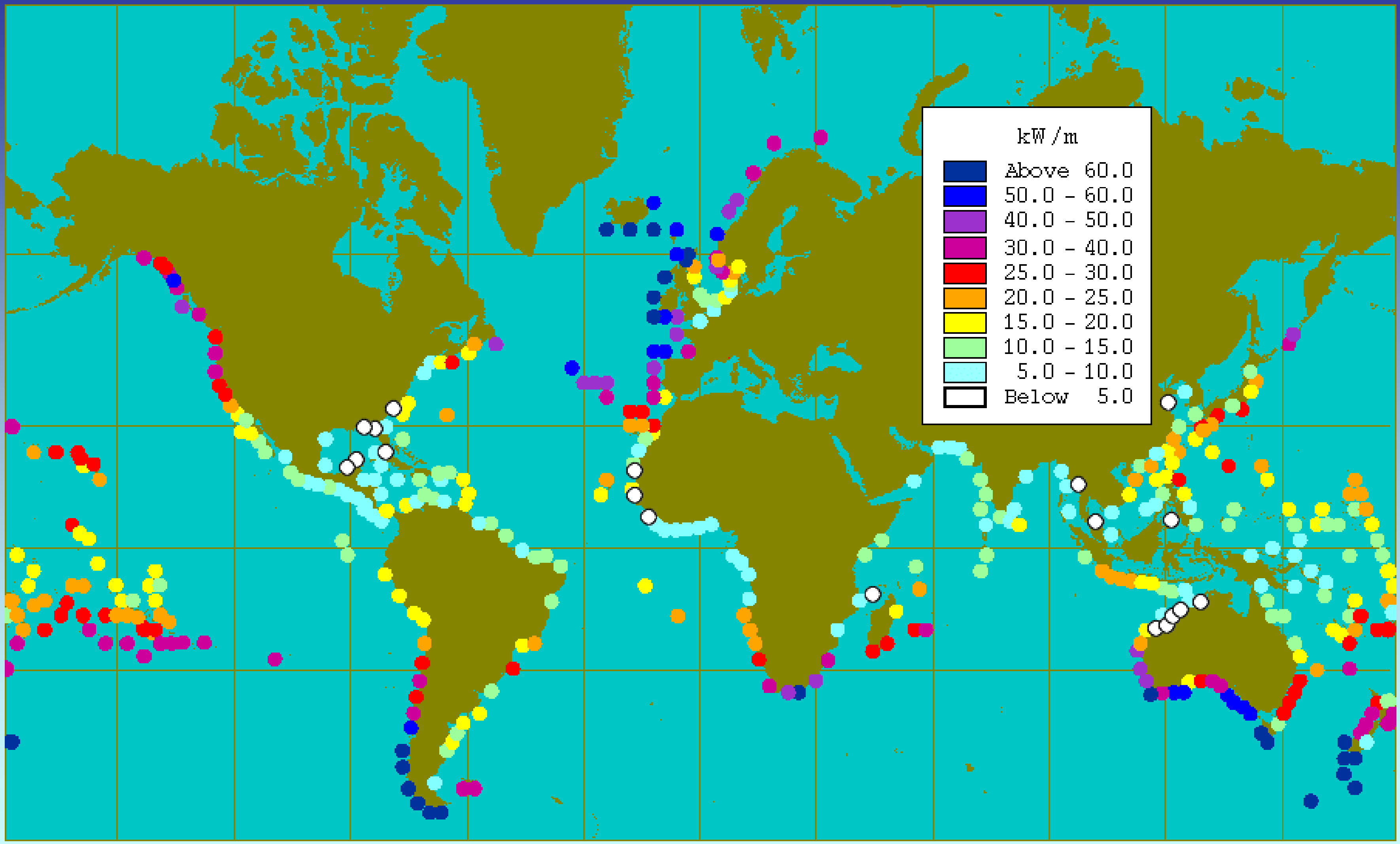

**Force 4** Wind Speed 11 to 16 knots (moderate breeze)
**Sea Criterion:** Small waves, becoming longer; fairly frequent white horses.

**Signif. Wave Height:** 1 to 1.5 m

**Peak Wave Period:** 4 to 5 sec

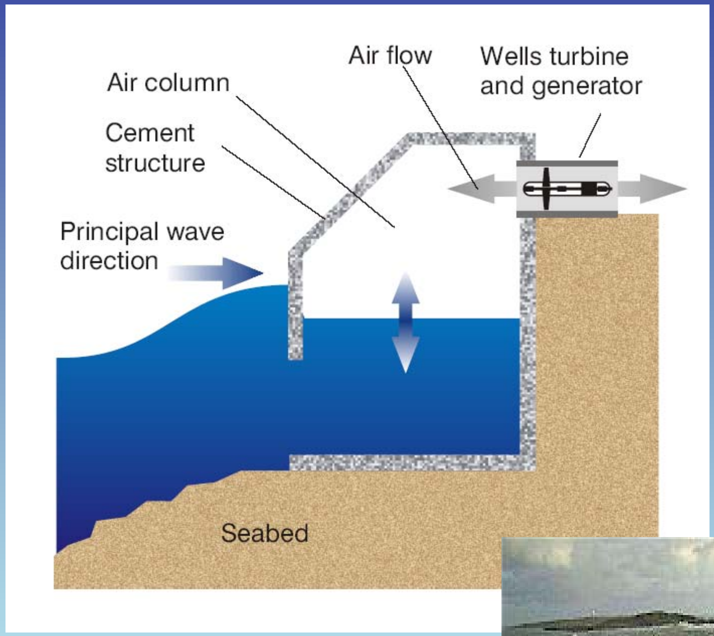
**Wave Energy Flux:** 2 to 6 kW/m

# Global Wave Energy Flux Distribution




There are few exposed coastlines with annual average wave energy fluxes less than 5 kW/m.

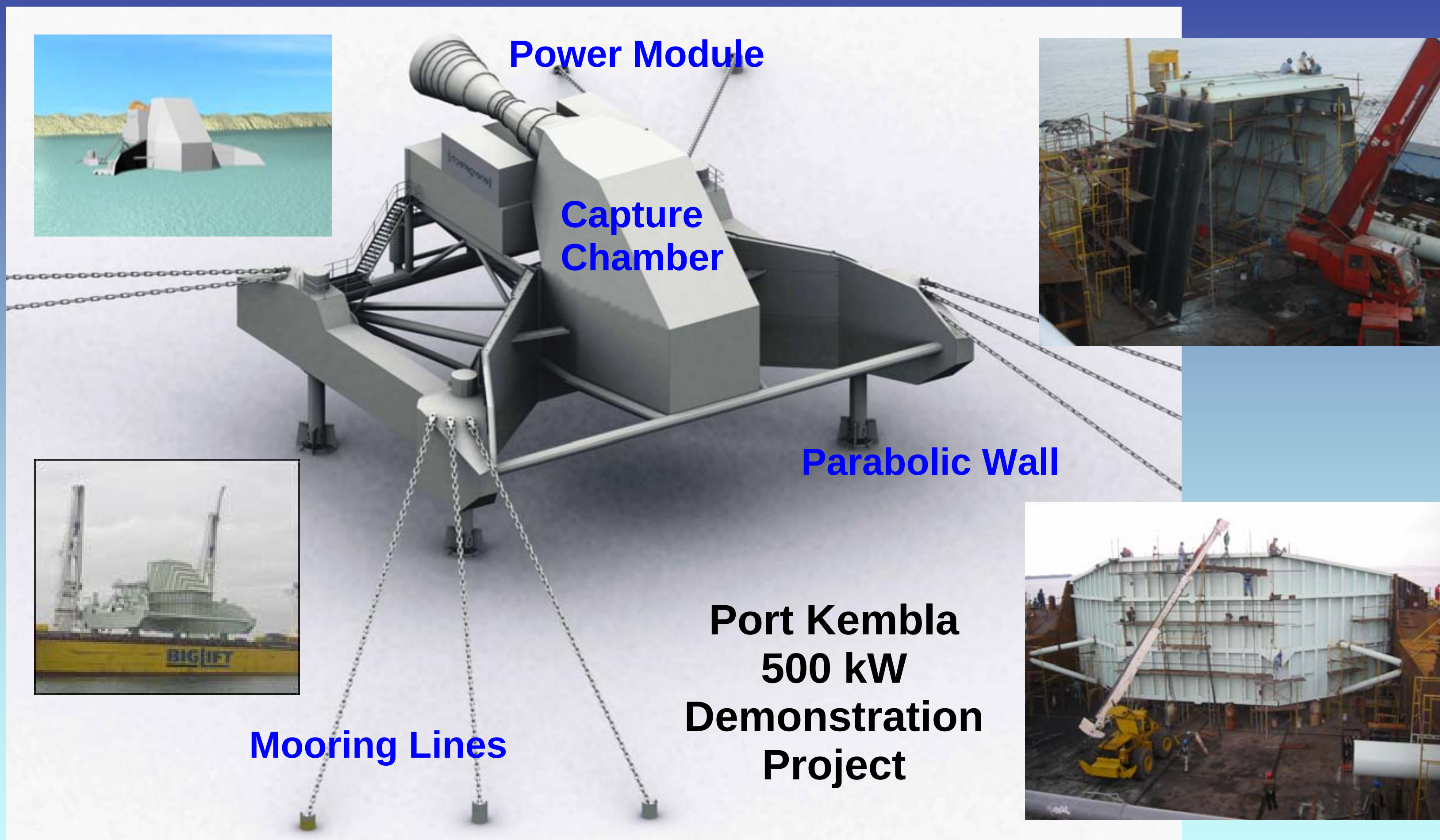
# OWC Terminator:  Onshore LIMPET



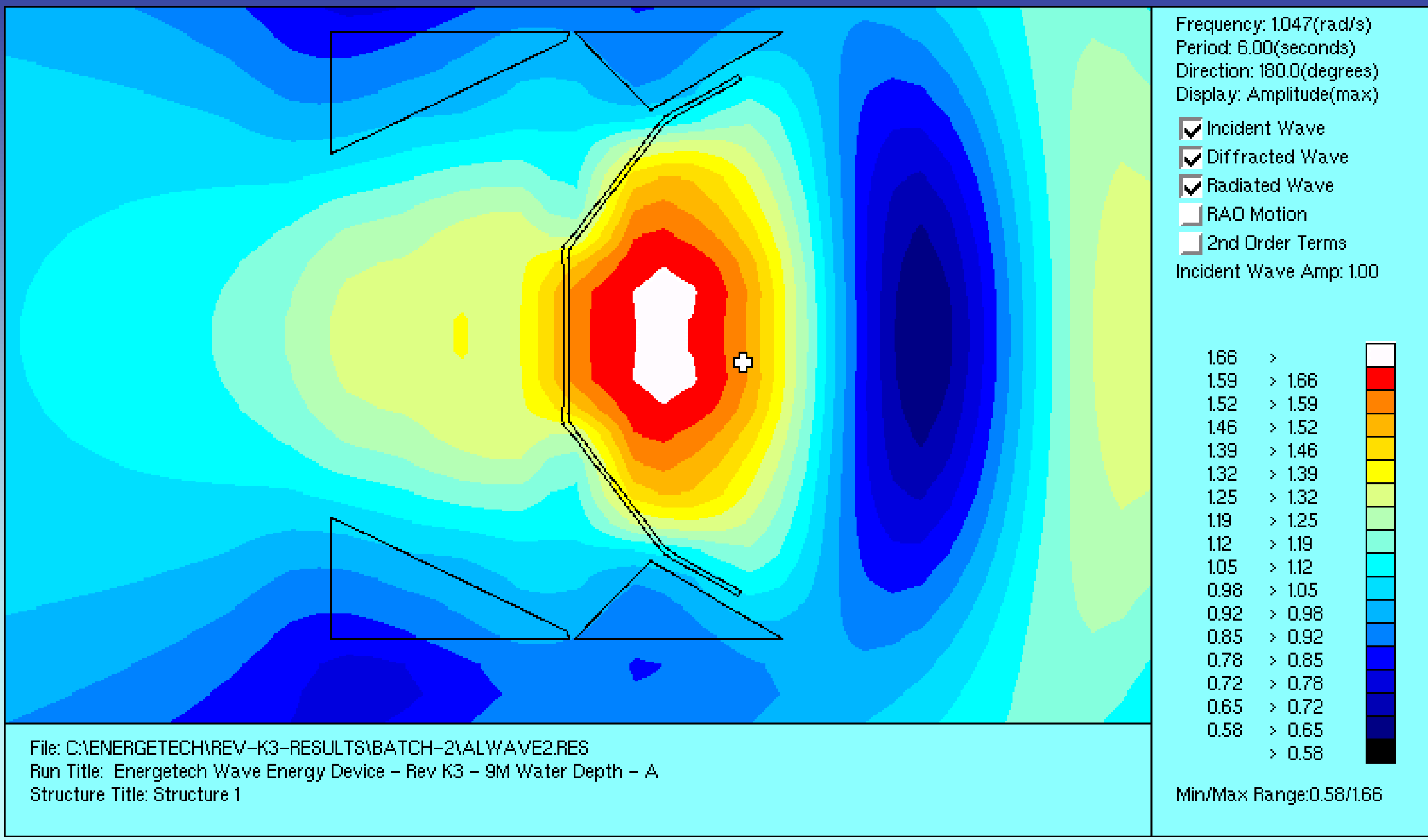

500 kW demonstration
project connected to utility
grid on Islay, Scotland
in November of 2000

Wavegen LIMPET:  Land-Installed Marine Powered Energy Transformer

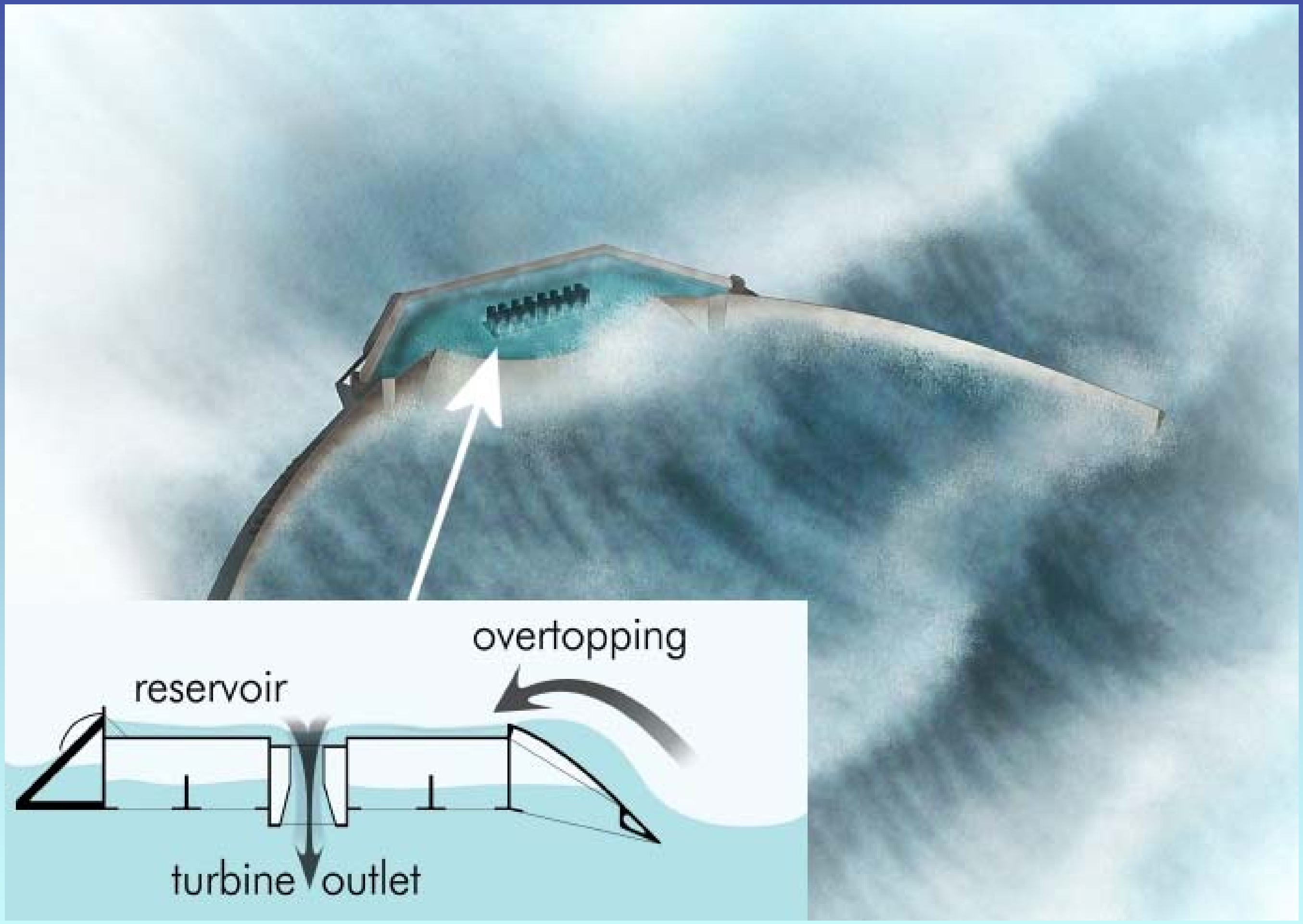
# OWC Terminator: Energetech's Nearshore Device



# Parabolic Wall Yields ~4x More Energy

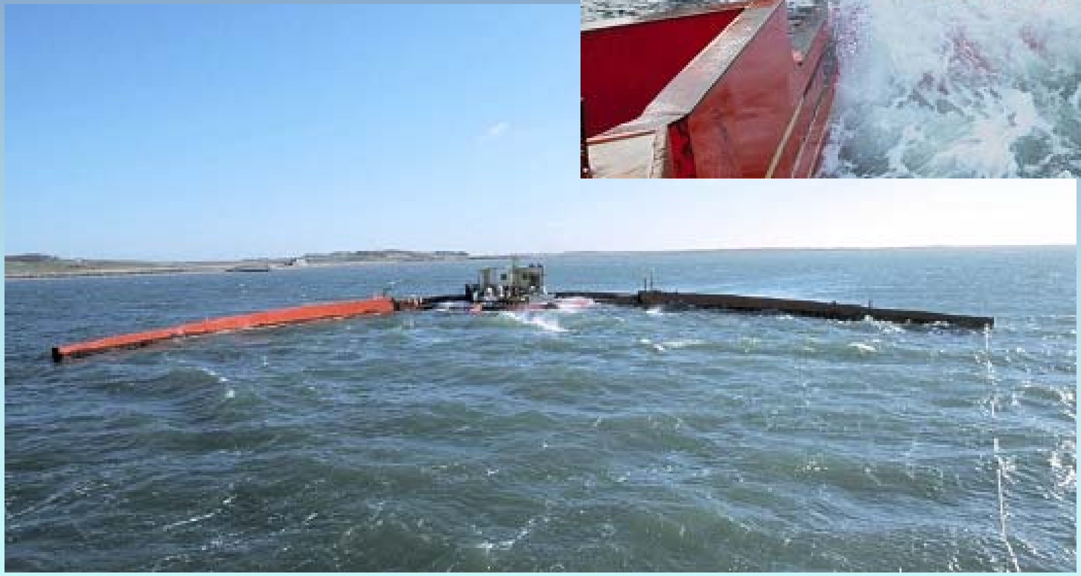


# Overtopping Terminator:  Wave Dragon



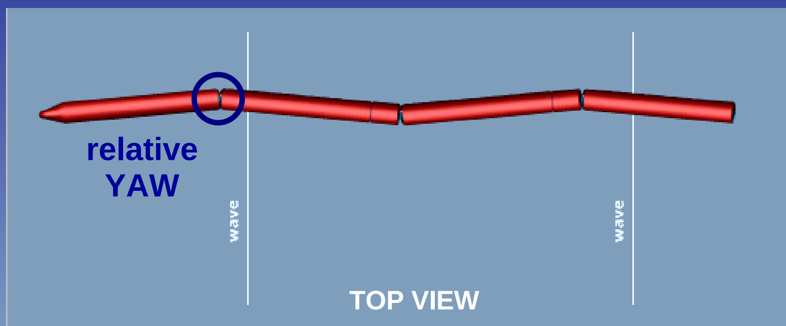
# Wave Dragon Prototype Trials

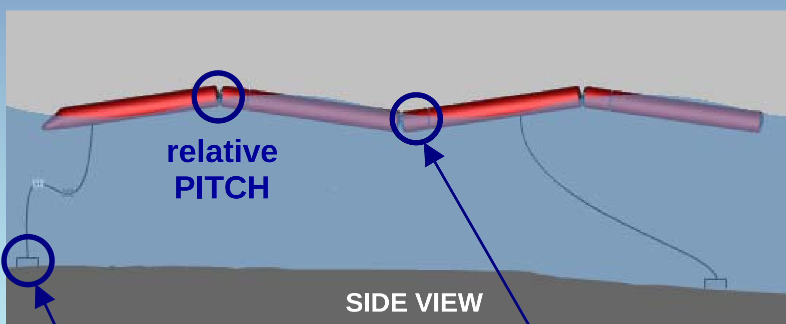
Prototype is 58 m wide (between tips of funneling side walls) and 33 m long, with a reservoir volume of 55 $m^3$ and a displacement of 237 metric tons. Total rated capacity is 17.5 kW.



Funneling side walls moored separately from central floating reservoir. Unexpected strong winds during installation caused damage to one of the side walls in half-deployed state.

# Floating Attenuator: Pelamis




**Bow mooring and power cable**

**Power module contains two hydraulic cylinders that are stroked by relative pitch and yaw between adjacent segments**

| Significant wave height ($H_{sig}$, m) \ Power period ($T_{pow}$, s) | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 9.5 | 10.0 | 10.5 | 11.0 | 11.5 | 12.0 | 12.5 | 13.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle | idle |
| 1.0 | idle | 22 | 29 | 34 | 37 | 38 | 38 | 37 | 35 | 32 | 29 | 26 | 23 | 21 | idle | idle | idle |
| 1.5 | 32 | 50 | 65 | 76 | 83 | 86 | 86 | 83 | 78 | 72 | 65 | 59 | 53 | 47 | 42 | 37 | 33 |
| 2.0 | 57 | 88 | 115 | 136 | 148 | 153 | 152 | 147 | 138 | 127 | 116 | 104 | 93 | 83 | 74 | 66 | 59 |
| 2.5 | 89 | 138 | 180 | 212 | 231 | 238 | 238 | 230 | 216 | 199 | 181 | 163 | 146 | 130 | 116 | 103 | 92 |
| 3.0 | 129 | 198 | 260 | 305 | 332 | 340 | 332 | 315 | 292 | 266 | 240 | 219 | 210 | 188 | 167 | 149 | 132 |
| 3.5 | - | 270 | 354 | 415 | 438 | 440 | 424 | 404 | 377 | 362 | 326 | 292 | 260 | 230 | 215 | 202 | 180 |
| 4.0 | - | - | 462 | 502 | 540 | 546 | 530 | 499 | 475 | 429 | 384 | 366 | 339 | 301 | 267 | 237 | 213 |
| 4.5 | - | - | 544 | 635 | 642 | 648 | 628 | 590 | 562 | 528 | 473 | 432 | 382 | 356 | 338 | 300 | 266 |
| 5.0 | - | - | - | 739 | 726 | 731 | 707 | 687 | 670 | 607 | 557 | 521 | 472 | 417 | 369 | 348 | 328 |
| 5.5 | - | - | - | 750 | 750 | 750 | 750 | 750 | 737 | 667 | 658 | 586 | 530 | 496 | 446 | 395 | 355 |
| 6.0 | - | - | - | - | 750 | 750 | 750 | 750 | 750 | 750 | 711 | 633 | 619 | 558 | 512 | 470 | 415 |
| 6.5 | - | - | - | - | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 743 | 658 | 621 | 579 | 512 | 481 |
| 7.0 | - | - | - | - | - | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 676 | 613 | 584 | 525 |
| 7.5 | - | - | - | - | - | - | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 686 | 622 | 593 |
| 8.0 | - | - | - | - | - | - | - | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 690 | 625 |

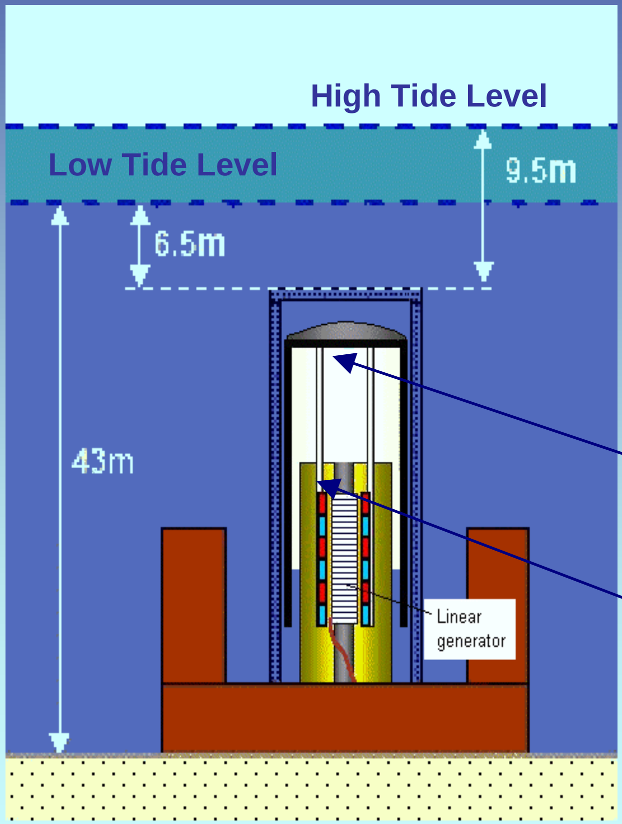

*Full-scale joint test rig at Edinburgh facility.*

# 750 kW Pelamis Demonstration Project


***Pelamis*** 750 kW prototype installed in August of 2004 in 50 m water depth, 2 km offshore the European Marine Energy Centre, Orkney, UK

# Point Absorber: Archimedes Wave Swing

**2 MW prototype deployed May 2004 off northern Portugal**



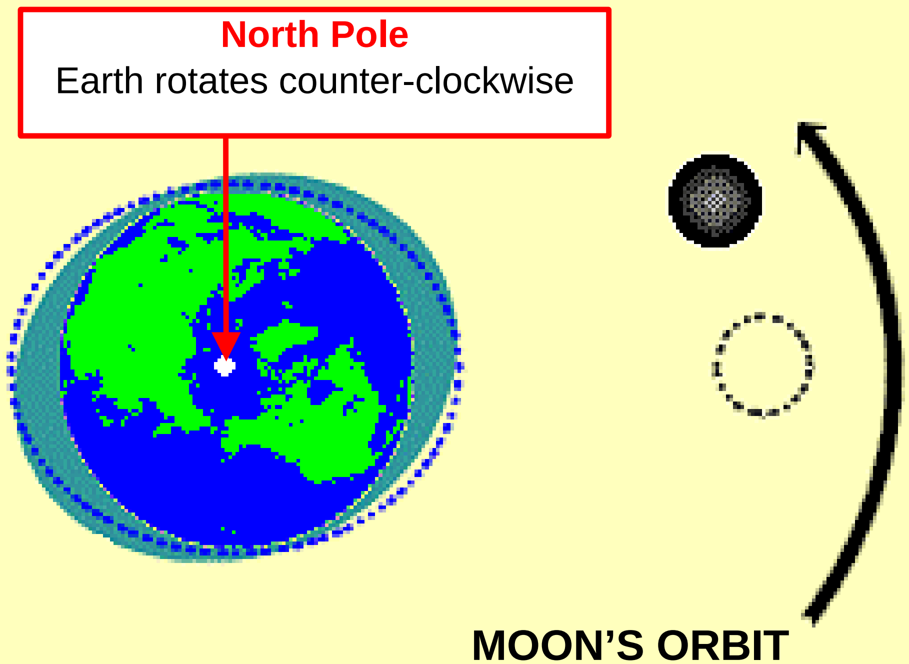

**Upper, air-filled floater heaves up and down in response to waves passing overhead.**

**Permanent magnets fixed to floater (suspended from overhead) move relative to stator coil on anchor base.**

# Lunar Tidal Period is 24 Hours *+ 50 Minutes*

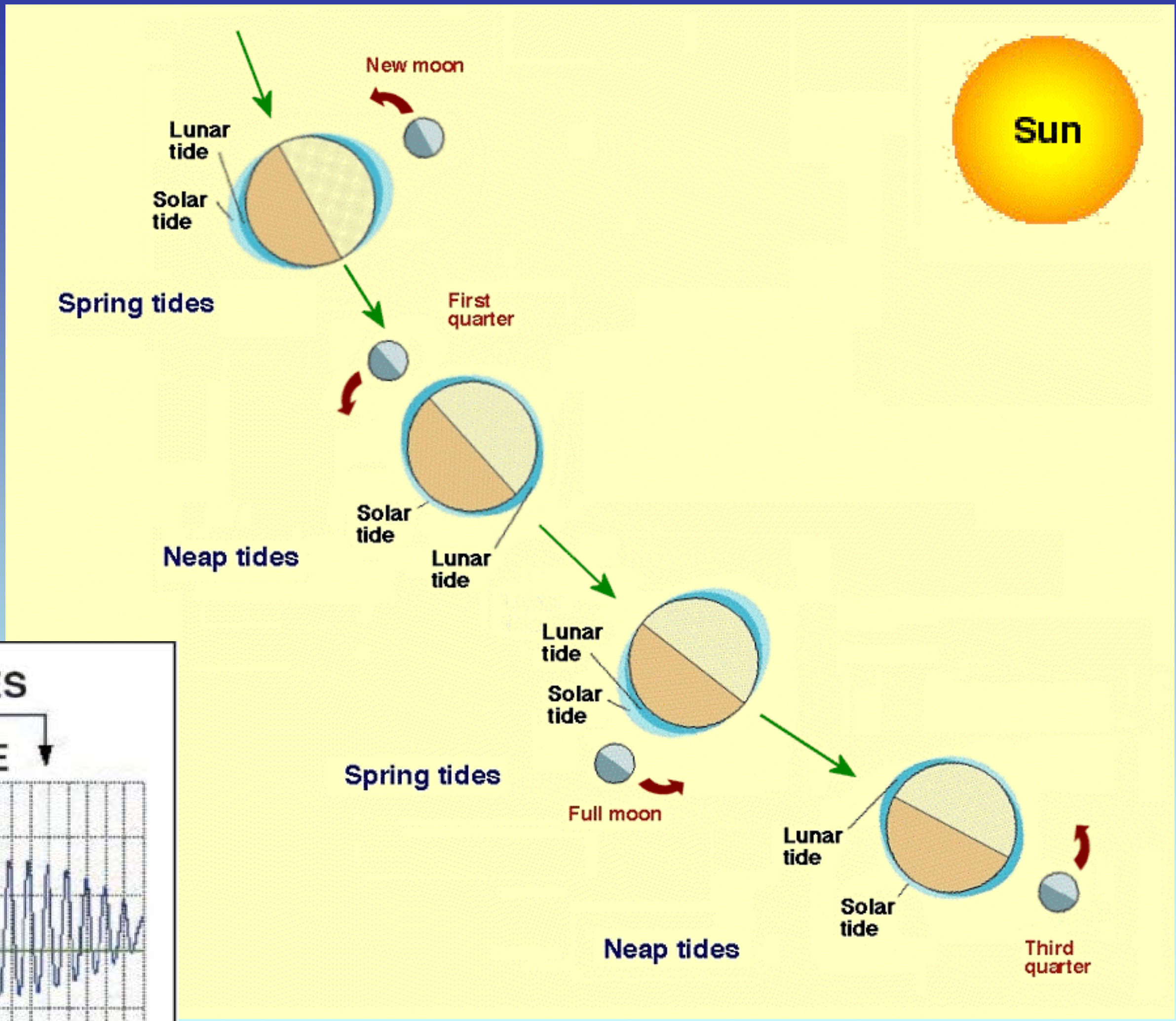
**Although it appears that the tidal bulge moves around the earth, the earth actually rotates beneath the lunar tidal bulge.**

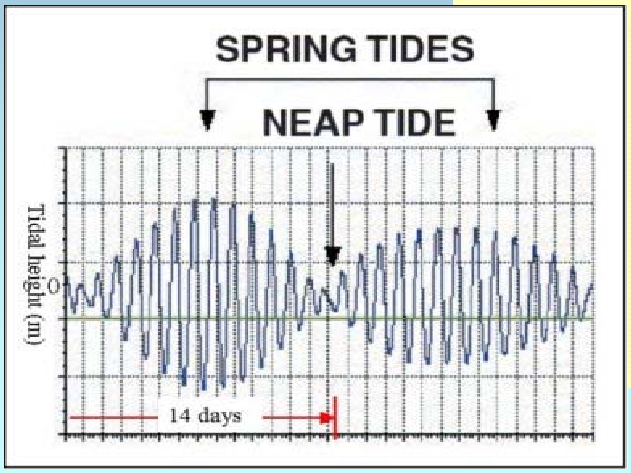
**While the earth completes one daily rotation, the moon progresses slightly in its 27.3-day orbit around the earth. As a result, the earth must rotate an additional 50 minutes before any given location "catches up" with the lunar bulge.**



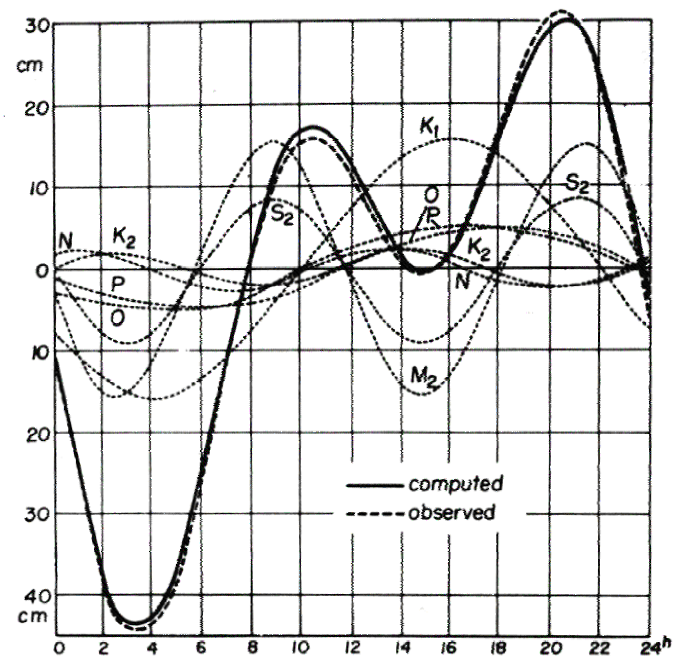
# Earth-Moon-Sun Tidal Forces

The solar tidal bulge is only 46% as high as the lunar tidal bulge. While the lunar bulge migrates around the Earth once every 27 days; the solar bulge migrates around the Earth once every 365 days. As the lunar bulge moves into and out of phase with solar bulge, this gives rise to spring and neap tides.



# Predicting Tides and Tidal Currents

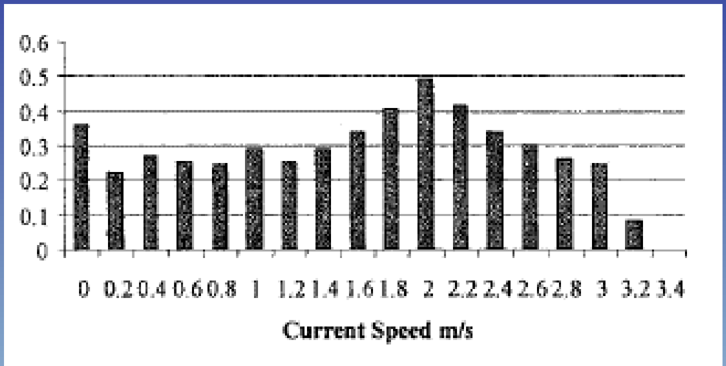



The Most Important of the Tide-generating Constituents (*After* Defant, 1958)

| SYMBOL | PERIOD (SOLAR HR) | AMPLITUDE ($M_2$ = 100) | DESCRIPTION |
|---|---|---|---|
| $M_2$ | 12.42 | 100.0 | Main lunar semidiurnal constituent |
| $S_2$ | 12.00 | 46.6 | Main solar semidiurnal constituent |
| $N$ | 12.66 | 19.1 | Lunar constituent due to monthly variation in moon's distance |
| $K_2$ | 11.97 | 12.7 | Solar-lunar constituent due to changes in declination of sun and moon throughout their orbital cycle |
| $K_1$ | 23.93 | 58.4 | Solar-lunar constituent |
| $O$ | 25.82 | 41.5 | Main lunar diurnal constituent |
| $P$ | 24.07 | 19.3 | Main solar diurnal constituent |
| $M_f$ | 327.86 | 17.2 | Moon's fortnightly constituent |

A minimum site-specific measured record length of 369 days is needed in order to capture all significant tide forcing components, the most important eight of which are shown above. *In the absence of strong onshore or offshore winds*, tide predictions based on harmonic analysis of measured sea level records are generally accurate to within 3 cm in terms of water level and 5 minutes in terms of tidal stage.

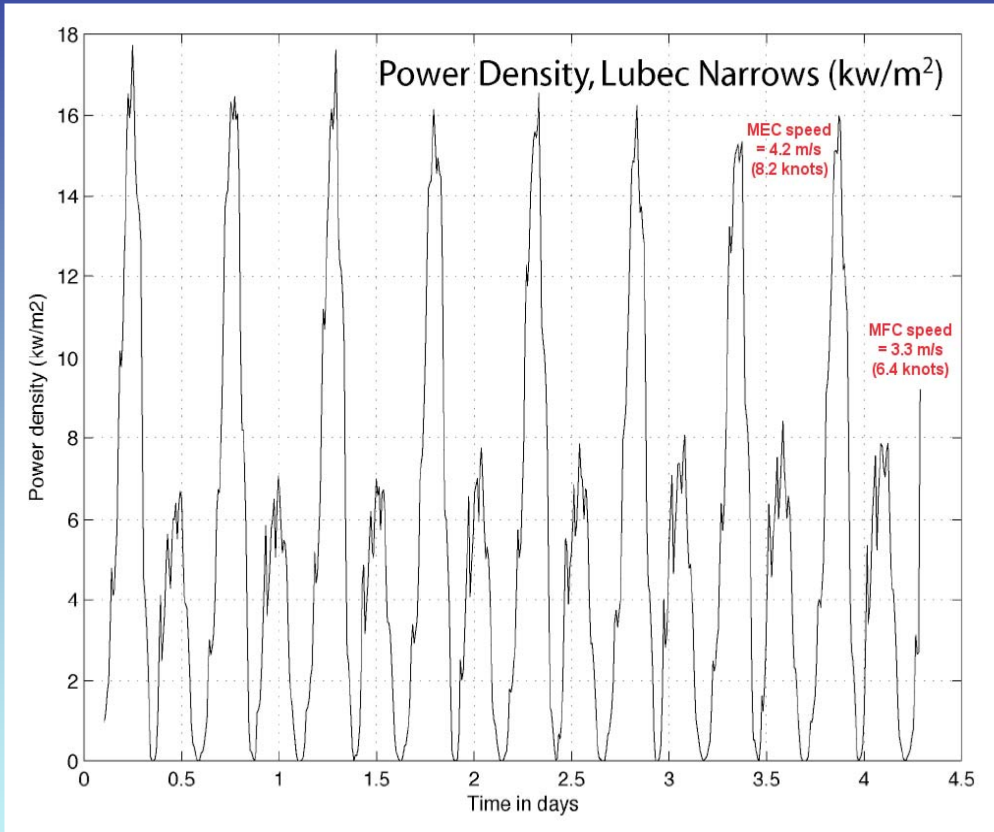
# Estimating Tidal In-Stream Energy Resources



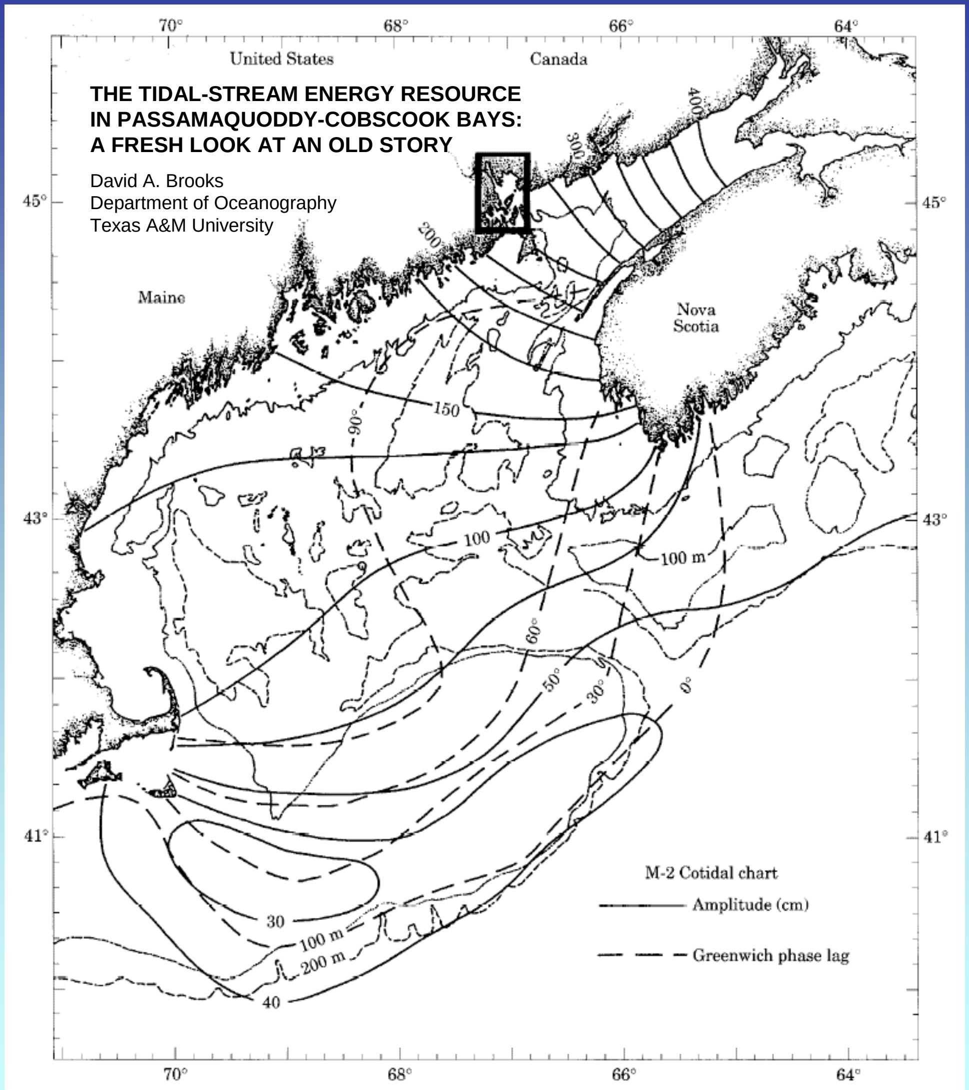

**Tidal Current Power Density**

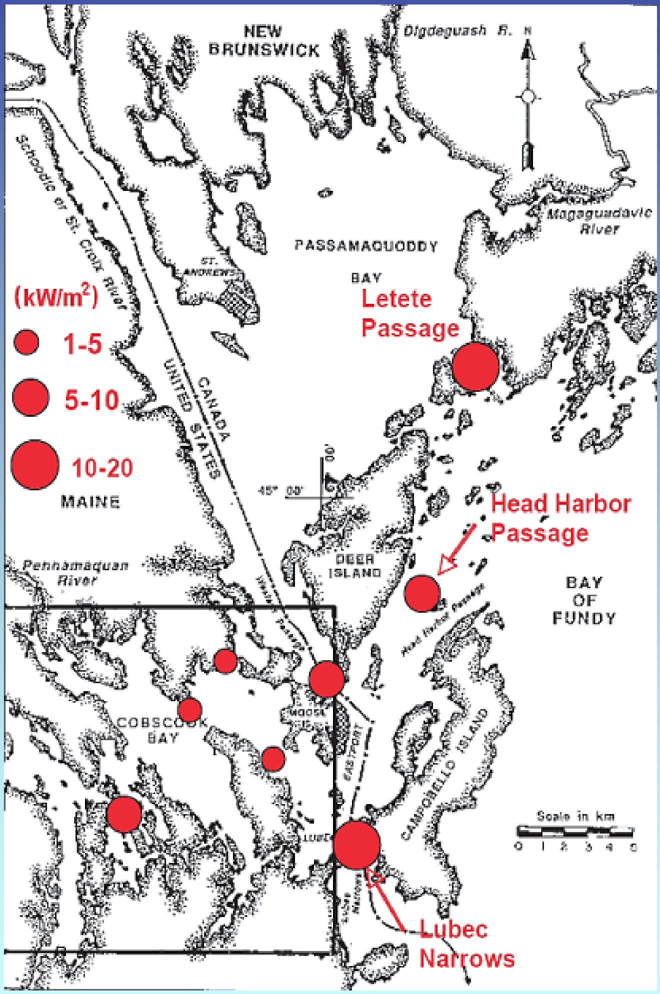
| $\rho$ (kg/m$^3$) | $V$ (knots) | $V$ (m/s) | $P/A_0$ (W/m$^2$) |
|---|---|---|---|
| 1,025 | 0.5 | 0.26 | 9 |
| 1,025 | 1.0 | 0.51 | 70 |
| 1,025 | 1.5 | 0.77 | 235 |
| 1,025 | 2.0 | 1.03 | 558 |
| 1,025 | 2.5 | 1.29 | 1,090 |
| 1,025 | 3.0 | 1.54 | 1,884 |
| 1,025 | 3.5 | 1.80 | 2,992 |
| 1,025 | 4.0 | 2.06 | 4,466 |

$$P(t) = 0.5 \rho A_o V^3(t)$$



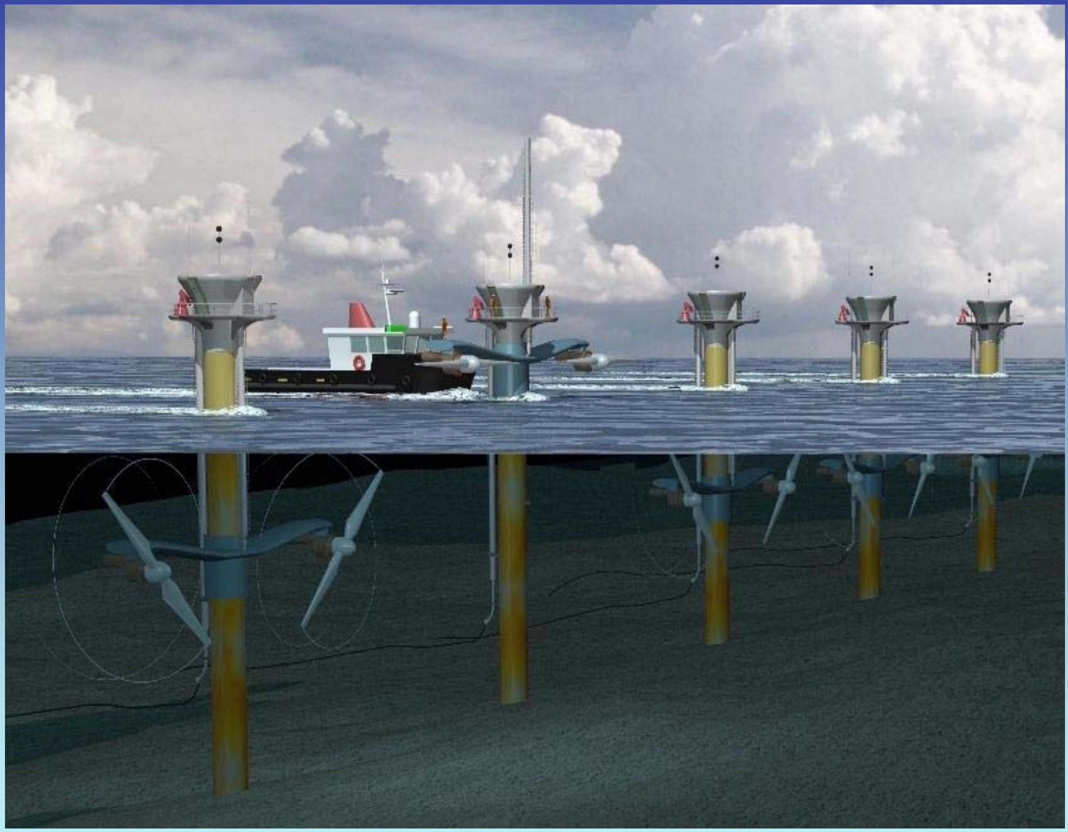
# Revisiting the Passamaquoddy Tidal Project



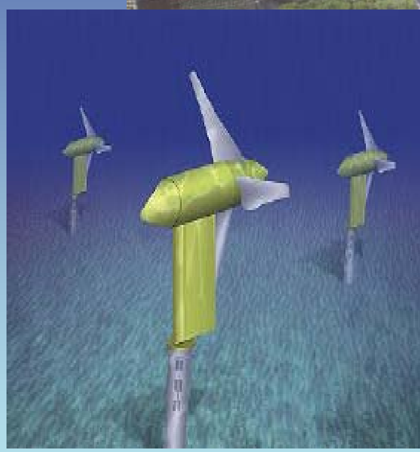
# UK-Based Marine Current Turbines


Marine Current Turbines
300 kW SeaFlow
(fully operational
since May 2003)

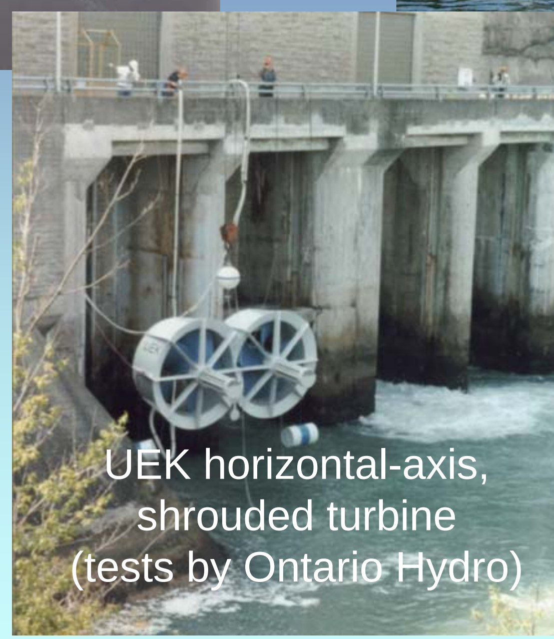


Marine Current Turbines
1.2 MW SeaGen
(single unit to be installed 2006)

# Tidal Stream Energy Devices in North America



Verdant Power horizontal-axis, (six-turbine, 200 kW test project to be installed in East River, NY)



UEK horizontal-axis, shrouded turbine (tests by Ontario Hydro)

GCK vertical-axis turbine (barge test on Merrimack River, MA)

# Renewable Energy Comparisons

| | Solar PV | Wind | Wave | Tidal Current |
|---|---|---|---|---|
| **Development Status** | Early Commercial | Commercial | Pre-Commercial | Pre-Commercial |
| **Source** | Sun | Uneven solar heating | Wind blowing over water | Gravity of moon & sun |
| **Annual Average Power Density** | 200-300 watts/m$^2$ (southern & western US) | 400-600 watts/m$^2$ (US Great Plains) | 20-25 kW/m (US West Coast)<br>5-15 kW/m (US East Coast) | 3-5 kW/m$^2$ (Bay of Fundy)<br>1-2 kW/m$^2$ (other US sites) |
| **Intermittency** | Day-night; clouds, haze, and humidity | Atmospheric fronts and storms (local winds only) | Sea (local winds) and swell (from distant storms) | Diurnal and semi-diurnal (advancing ~50 min./day) |
| **Predictability** | Minutes | Hours | Days | Centuries |

# EPRI North American Ocean Energy Projects

## Offshore Wave Energy Conversion (OWEC)

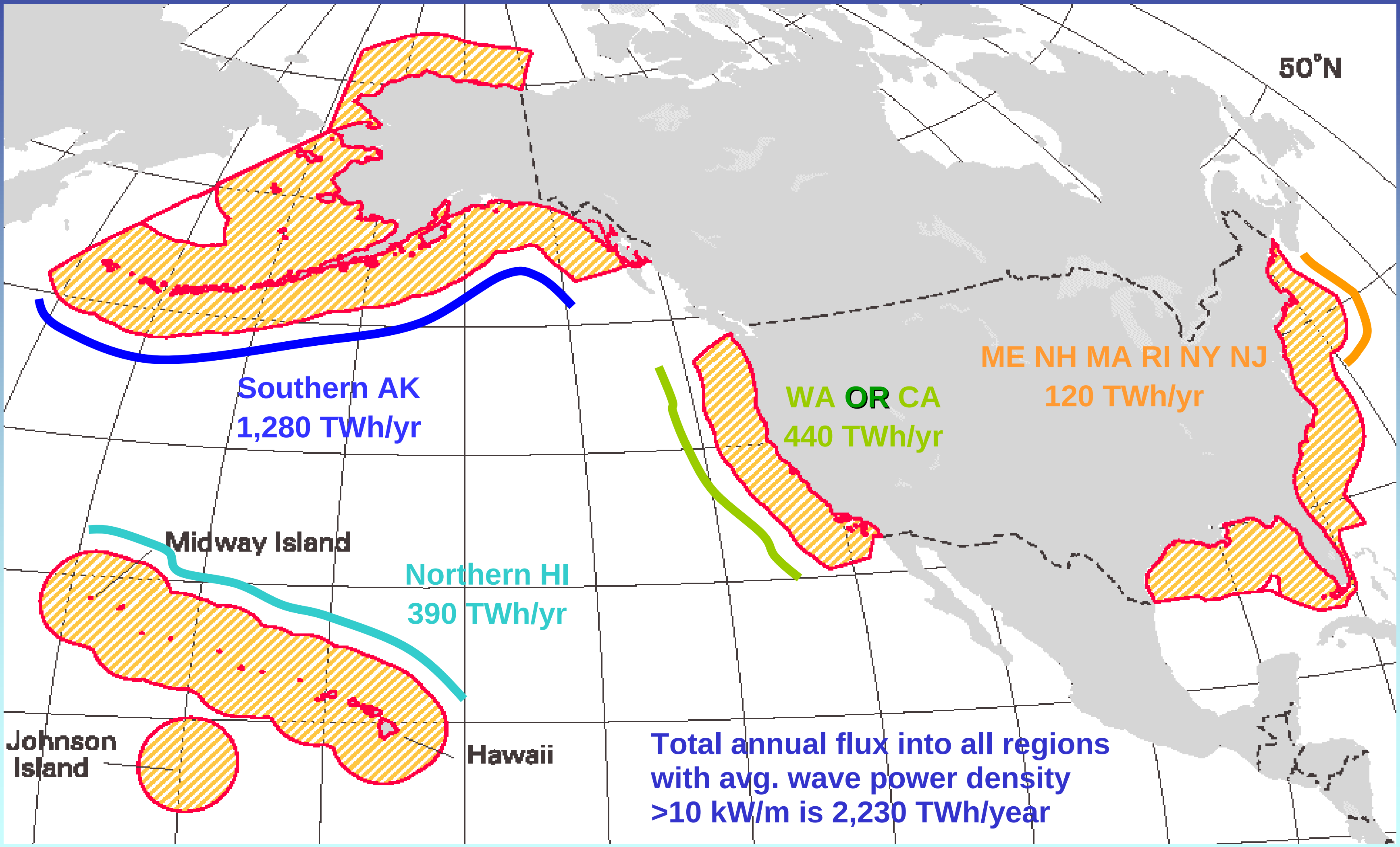
| Phase 1 Project Definition Study | Phase 1.5 Pre-Implementation Planning | Phase 2 Design, Permitting, & Financing | Phase 3 Construction | Phase 4 Operation & Evaluation |
|---|---|---|---|---|
| 2004 | 2005 | 2006 | 2007 | 2008 |

## Tidal In-Stream Energy Conversion (TISEC)

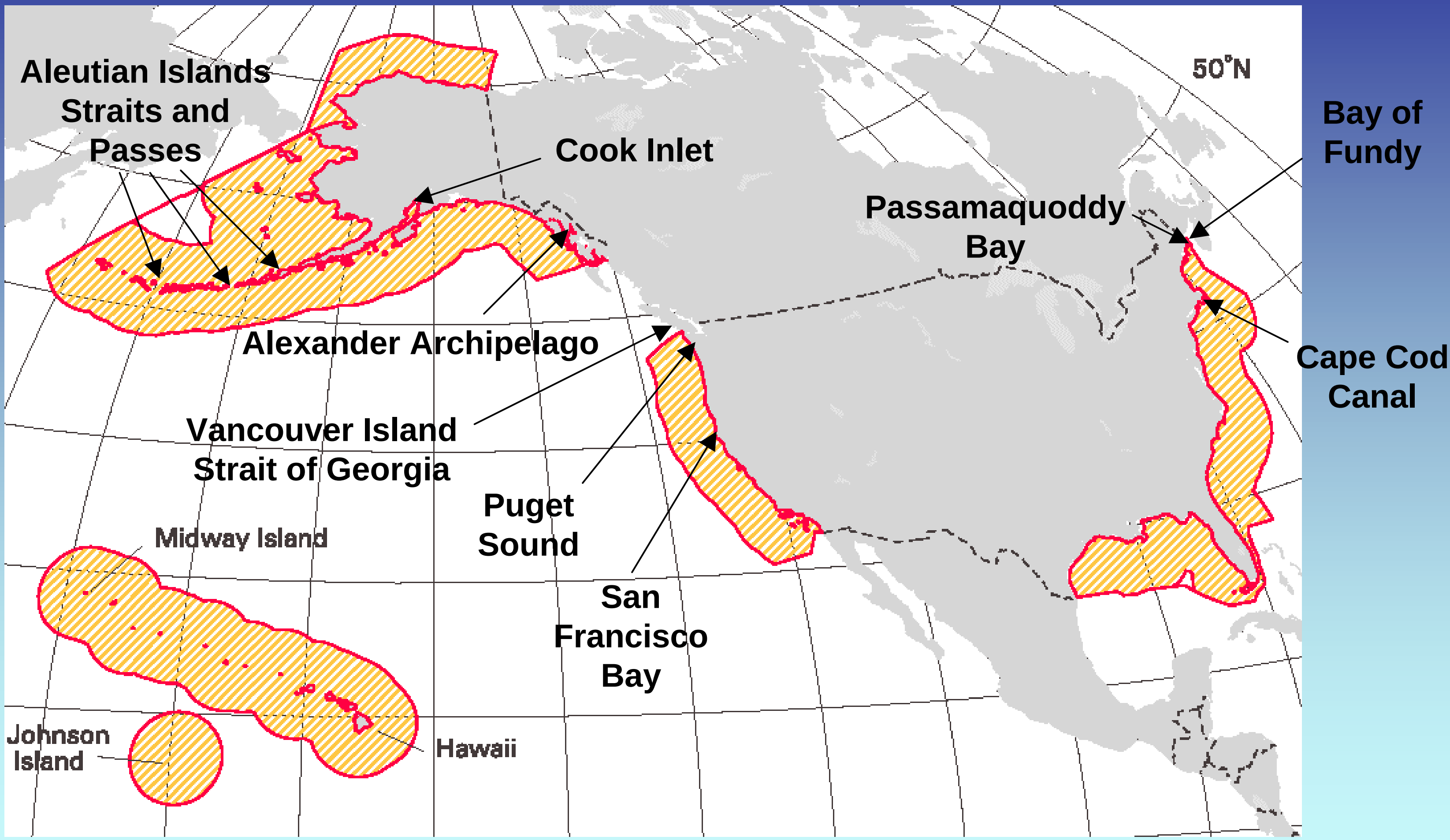
| Phase 1 Project Definition Study | Phase 1.5 Pre-Implementation Planning | Phase 2 Design, Permitting, & Financing | Phase 3 Construction | Phase 4 Operation & Evaluation |
|---|---|---|---|---|
| 2005 | 2006 | 2007 | 2009 | 2010 |

- Completed
- In-progress
- Future

# Offshore Wave Energy Resources in U.S. Exclusive Economic Zone



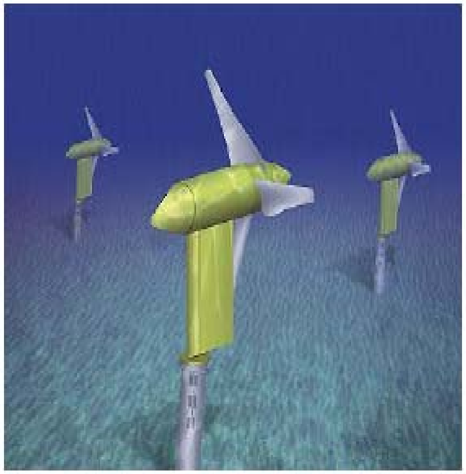
# Major North American Tidal In-Stream Energy Resources



# EPRI North American Tidal In-Stream Energy Conversion Feasibility Demonstration Project

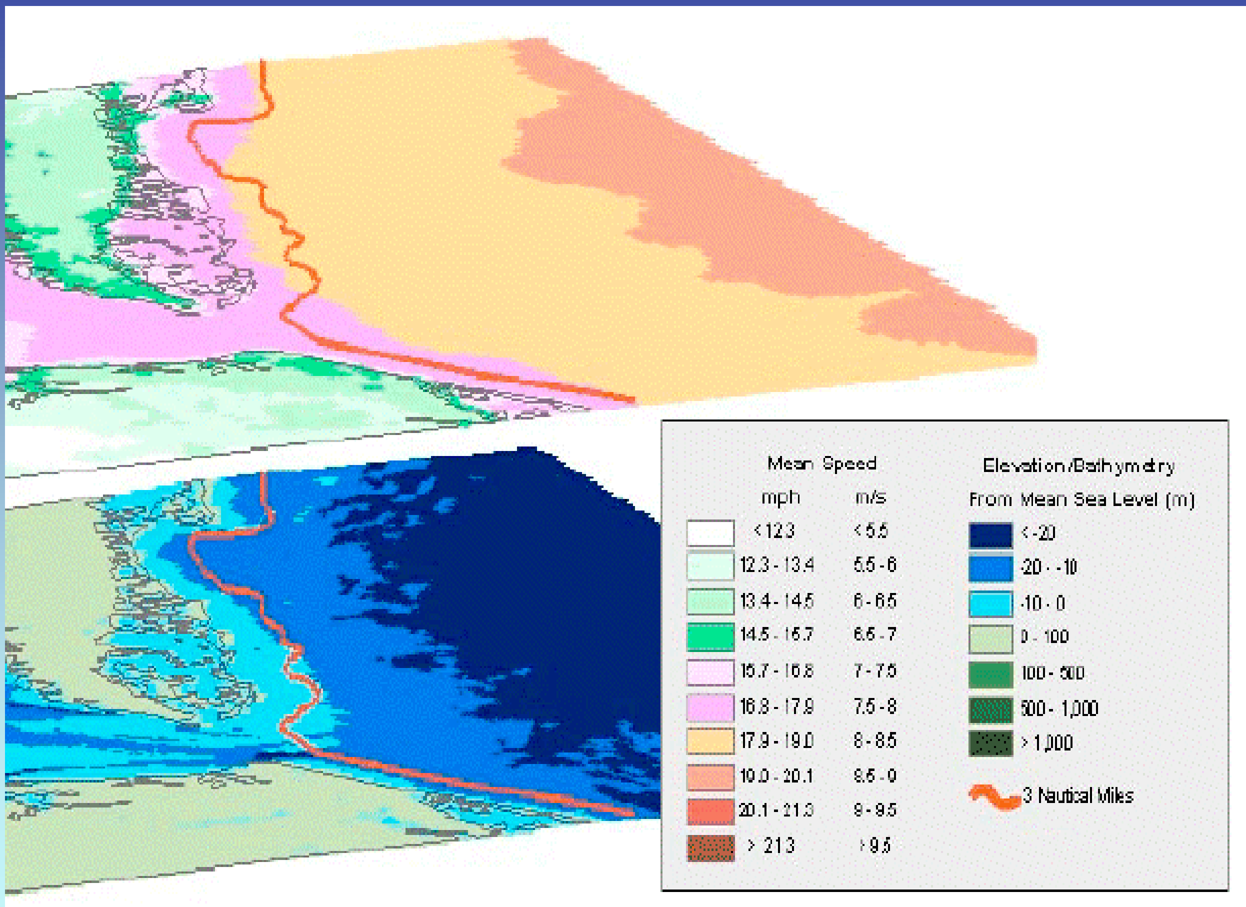
Objective

To demonstrate the feasibility of tidal in-stream power to provide efficient, reliable, environmentally friendly and cost-effective electrical energy and to create a push towards the development of a sustainable commercial market for this technology.



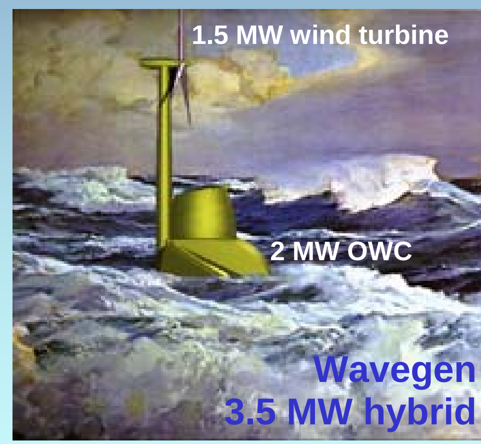
| Phase | Duration | Key Activities | Cost | Funding |
|---|---|---|---|---|
| Phase I – Project Feasibility Definition Study | 1 Year April 2005 to March 2006 | Site survey & characterization;<br>Technology / device survey;<br>Feasibility-level system design, performance analysis, life-cycle cost estimate and economic assessment;<br>Environmental, regulatory and permitting issues | $350K | Maine<br>Massachusetts<br>New Brunswick<br>Nova Scotia<br>DOE<br>EPRI<br>San Francisco<br>Alaska<br>Washington |
| Phase II – System Design | 12-18 Months | System Design, permitting and financing - 1 Site – Device | $500-1,000 K | Private owner or collaborative |
| Phase III - Construction | 12 - 18 Months | 1,500 MWh per year Plant (500 kW at 40% capacity factor) | $1,500 - 2,700 K | Private owner or collaborative |
| Phase IV - Operation | 1-2 Years | Plant O&M costs | $100-250K | Private owner or collaborative |
| Phase IV - Evaluation | 1-2 Years | Additional cost due to RD&D needs | $100-250K | 50% DOE<br>50% EPRI |
| **Total** | **5 - 7 Yrs** | | **$3-5 M** | |

# EPRI North American Hybrid Offshore Wind and Wave Energy Demonstration Proposal




**Advantages:**

- Not visible from shore
- Shared foundation and submarine cable costs
- Greater wind and wave power densities
- Greater continuity of output -- yesterday's winds are today's waves




Off Virginia, 3-mile limit of state jurisdiction roughly corresponds to 10 m water depth contour. In deeper waters "over the horizon," mean annual wind power is 400-500 watts/m$^2$ of rotor swept area at 70 m hub height, and mean annual wave power is 4-5 kW/m of wave crest width.